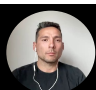
MODULE 1: ULTRASOUND FOUNDATIONS (PHYSICS + INSTRUMENTATION)

Carlos Jimenez Phd (c), DPT, RMSK, CPSS

1



Ultrasound Foundations: Physics, Image Optimization, and MSK Relevance

- Why this matters:
- Image clarity
- Artifact recognition
- Safe scanning
- The bridge between **good scanning** and **diagnostic confidence**

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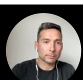
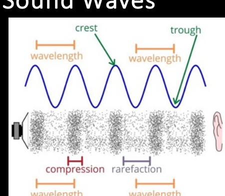


Ultrasound = Mechanical Longitudinal Sound Waves”

- Mechanical, not electromagnetic
- Requires a medium
- Travels as **compression & rarefaction**
- Frequency >20,000 Hz

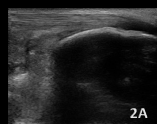


3

Frequency = Resolution vs Penetration

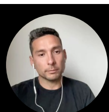
- ↑ Frequency → ↑ resolution, ↓ depth
- ↓ Frequency → ↓ resolution, ↑ depth

- Clinical examples:
- 15–18 MHz: tendons, ligaments, nerves
- 6–8 MHz: deep hip, proximal hamstring

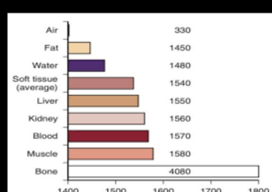


4

Speed of Sound in Soft Tissue = 1540 m/s

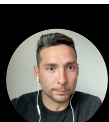


- Ultrasound machines assume one speed
- Incorrect assumption → artifacts
- Variable tissues:
  - Fat slower
  - Tendon faster
  - Bone fastest (major reflector)

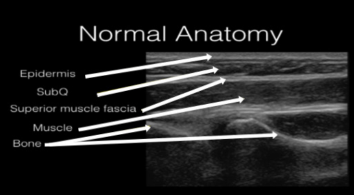


5

Why Some Structures Look Bright or Dark



- Impedance = density × speed
- High mismatch → strong reflection (bright)
- Low mismatch → weak reflection (dark)



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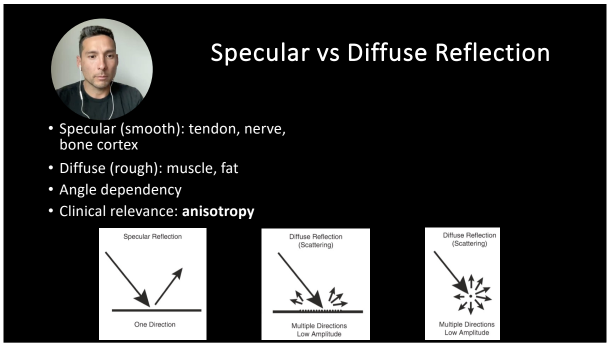
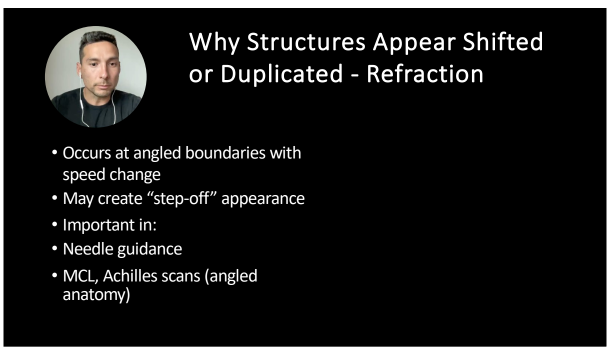
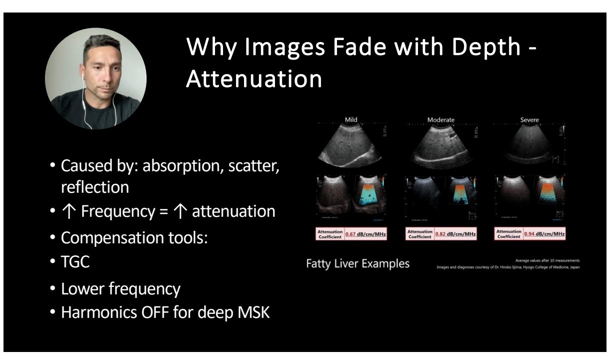

Specular vs Diffuse Reflection
• Specular (smooth): tendon, nerve, bone cortex
• Diffuse (rough): muscle, fat
• Angle dependency
• Clinical relevance: **anisotropy**
Specular Reflection
One Direction
Diffuse Reflection (Scattering)
Multiple Directions Low Amplitude
Diffuse Reflection (Scattering)
Multiple Directions Low Amplitude

7


Why Structures Appear Shifted or Duplicated - Refraction
• Occurs at angled boundaries with speed change
• May create “step-off” appearance
• Important in:
• Needle guidance
• MCL, Achilles scans (angled anatomy)

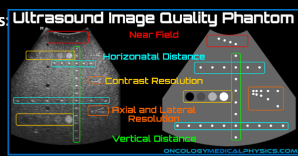
8


Why Images Fade with Depth - Attenuation
• Caused by: absorption, scatter, reflection
• ↑ Frequency = ↑ attenuation
• Compensation tools:
• TGC
• Lower frequency
• Harmonics OFF for deep MSK
Mild
Moderate
Severe
Attenuation Coefficient 0.67 dB/cm/MHz
Attenuation Coefficient 0.82 dB/cm/MHz
Attenuation Coefficient 0.94 dB/cm/MHz
Fatty Liver Examples
Average values after 10 measurements
Images and diagnoses courtesy of Dr. Hiroko Iijima, Hyogo College of Medicine, Japan

9

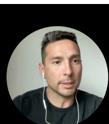
Lateral, Axial, Elevational Resolution

How Sharp Your Image Actually Is:



- Axial = along beam → best resolution
- Lateral = perpendicular → depends on focusing
- Elevational = slice thickness → **bursa vs tendon artifact**

10



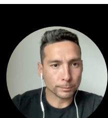
Transducers

Why Linear Probes Dominate MSK

- Linear probe: high frequency, rectangular field
- Curvilinear: deep hip, glute, proximal hamstring
- Keep the footprint perpendicular

Image	Probe Type	Frequency (MHz)	Use Case
	Linear	10–17 MHz	Superficial structures: tendons, muscles, ligaments (e.g., wrist, quad tendon)
	Curvilinear	3–7 MHz	Deeper structures: abdomen, hips
	Compact Linear	15–17 MHz	Small areas: fingers, toes, dynamic MSK
	Phased Array	2–5 MHz	Cardiac or deep thoracic

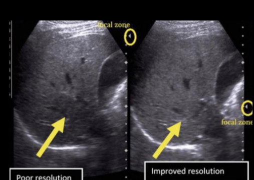
11



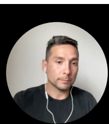
Focusing

Place the Focal Zone at the Structure of Interest

- Improves lateral resolution
- Narrowest beam = sharpest point
- Multiple focal zones slow frame rate



12

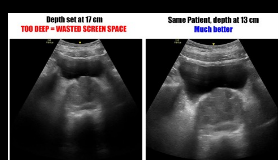


The Controls You Actually Need to Master

- Depth
- Gain
- TGC
- Frequency
- Dynamic Range
- Focus
- Harmonics
- Compound imaging

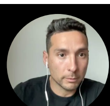
13

Set Depth for the Smallest Field That Fits the Anatomy



- Too deep = tiny structure
- Too shallow = anatomy cut off
- Ideal: structure centered in screen middle third

14

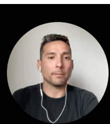


Gain & TGC

Brightness Should Match Tissue Realism

- Gain = global brightness
- TGC = depth-specific
- Avoid "over-gaining tendons"

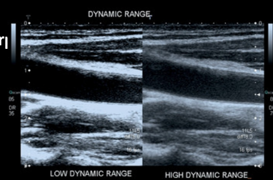
15



Dynamic Range

Contrast Control: How Soft or Shar

- High DR = smooth, low contrast
- Low DR = crisp, high contrast
- Useful for: nerves, tendons

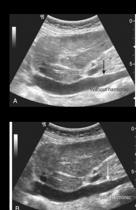


16

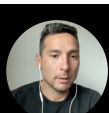
Harmonics & Compound Imaging

When Advanced Modes Help — and When They Hurt

- Harmonics ON: improves clarity in superficial structures
- Harmonics OFF: needed for deeper structures
- Compound imaging: reduces noise, reduces artifacts

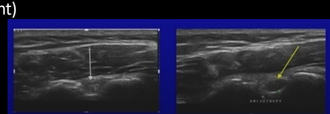


17



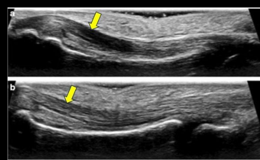
Artifacts Are Not Errors — They Are Clues

- Anisotropy (most important)
- Shadowing
- Acoustic enhancement
- Reverberation
- Side lobe artifact



18

Anisotropy (Deep Dive)



Angle-Dependent Brightness Loss — Not Pathology

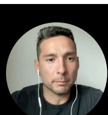
- Occurs with tendons & nerves
- Beam must be perpendicular
- Fix = heel-toe maneuver

19

Ultrasound Safety Principles: ALARA, MI, TI, and Doppler Output

- Safe → Effective → Evidence-Based MSK Scanning
- Understanding output keeps MSK practice aligned with POCUS & RMSK standards

20



ALARA = As Low As Reasonably Achievable

- Use lowest output for diagnostic image
- Limit unnecessary dwell time
- Use appropriate presets

21

Mechanical Index (MI) — Risk of Cavitation

- MI relates to **acoustic pressure** + **frequency**
- High MI = more cavitation potential
- MSK scanning = **naturally very low MI**

22

Thermal Index (TI) — Risk of Tissue Heating

- TI predicts possible temperature rise
- TIS = soft tissue TI
- TIB = bone TI (higher near cortex)
- MSK TI stays very low

23

Doppler = Increased Acoustic Power

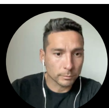
- Color & spectral Doppler raise MI & TI
- Use Doppler **purposefully and briefly**
- Essential applications in MSK:
- Neovascularity (Achilles, patellar)
- Hyperemia
- Vascular injury assessment

24

Simple Rules for Safe & Effective MSK Ultrasound

- Use appropriate MSK presets (low output, high frequency)
- Keep probe moving unless clinically necessary
- Use Doppler sparingly and purposefully
- Follow ALARA: image quality → minimal power
- Monitor MI/TI but know MSK values stay low

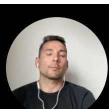
25



Module 1 References — Physics, Instrumentation & Safety

Hedrick WR et al. *Ultrasound Physics and Instrumentation.* Elsevier; 2013.
Kremkau FW. *Diagnostic Ultrasound: Principles and Instruments.* Elsevier; 2020.
Hoskins PR et al. *Diagnostic Ultrasound: Physics and Equipment.* CRC Press; 2019.
Jacobson JA. *Fundamentals of Musculoskeletal Ultrasound.* 3rd ed. Elsevier; 2018.
Smith J, Finnoff JT. *PM&R.* 2009;1(1):64–75.
AIUM. *Official Statement on Ultrasound Safety.*
WFUMB. *Global Guidelines on Ultrasound Safety.*
Barnett SB et al. *Safe Use of Ultrasound in Medical Diagnosis.* BIR; 2012.
Bassignani MJ. *Ultrasound Clinics.* 2007.
- Fessell DP, van Holsbeeck M. *Ultrasound Clinics.* 2007.

26



MODULE 2 — Ultrasound Propagation, Tissue Interaction & Artifacts

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27

Ultrasound Propagation, Tissue Interaction & Artifacts

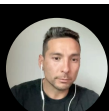
- Acoustic Impedance
- Reflection / Scattering / Refraction
- Attenuation
- Tissue Echogenicity
- Key MSK Artifacts

28

Correct Interpretation Depends on Understanding Wave Behavior

- Image clarity
- Identifying true pathology
- Fixing artifacts
- Accurate tendon, ligament, nerve evaluation

29



Acoustic Impedance (Z)

Why Different Structures Appear Light or Dark

- Z = density × speed
- Bigger mismatch → stronger reflection
- Examples:
- Bone vs soft tissue = bright cortex + shadow
- Tendon vs muscle = strong interface echo

Material	Density ρ (kgm^{-3})	Speed c (ms^{-1})	Characteristic impedance Z ($kgm^{-2}s^{-1}$) × 10^6
Water	1000	1480	1.5
Blood	1060	1570	1.62
Bone	1380–1810	4080	3.75-7.38
Brain	1030	1558	1.55–1.66
Fat	920	1450	1.35
Kidney	1040	1560	1.62
Liver	1060	1570	1.64–1.68
Lung	400	650	0.26
Muscle	1070	1584	1.65–1.74
Spleen	1060	1566	1.65–1.67

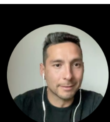
30

Reflection (Primary Image Creator)

Reflection = The Echoes We Turn Into Images

- Specular → tendon, bone cortex
- Diffuse → muscle, fat
- Angle-dependent (critical for MSK)

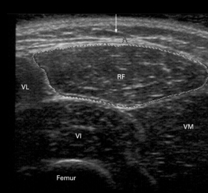
31



Scattering

Why Muscle Looks Grainy or Speckled

- Irregular surfaces
- Multi-direction echoes
- Creates characteristic MSK texture

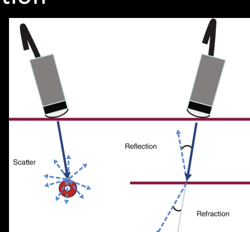


32

Refraction

Beam Bending = Misplaced or Duplicated Structures

- Occurs when beam crosses angled tissue with different speed
- Can shift structures or create step-off
- Seen around tendons, MCL, Achilles

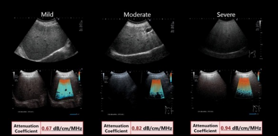


33

Attenuation

Why Structures Darken With Depth

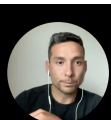
- Caused by absorption, scatter, reflection
- Stronger in: muscle → tendon → bone
- Higher frequency = more attenuation



Fatty Liver Examples

Average values after 10 measurements
Images and diagnoses courtesy of Dr. Hiroko Iijima, Hyogo College of Medicine, Japan

34



Echogenicity Patterns

How Each MSK Tissue Normally Appears

- **Bone:** bright cortex, clean shadow
- **Tendon:** fibrillar, bright
- **Muscle:** pennate, hypoechoic with fibroadipose septa
- **Ligament:** linear, compact
- **Nerve:** honeycomb pattern
- **Fat:** hypoechoic with striations

35

Bone

Impedance Wall: Strongest Reflector

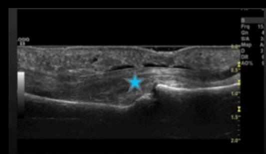
- 99% reflection
- No through-transmission
- Posterior shadow → diagnostic

36

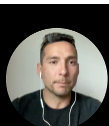
Tendon

Highly Organized, Highly Reflective

- Hyperechoic fibrillar
- Strong angle dependency
- Susceptible to anisotropy



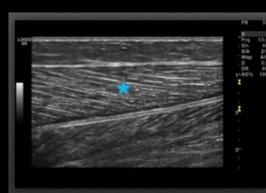
37



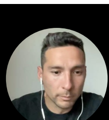
Muscle

Pennate Architecture + Scatter + Hypoechoic Tissue

- Hypoechoic muscle fibers
- Hyperechoic septa
- Pennation angle changes with contractio



38



Nerves

Honeycomb in Short Axis, Fascicular in Long Axis

- Fascicles hypoechoic
- Perineurium hyperechoic
- Angle sensitive (mild anisotropy)

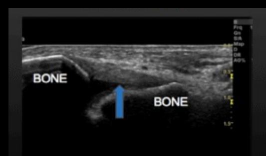
39

Ligaments

"Compact, Hyperechoic Bands with Linear Fibers"

On Slide:

- Less anisotropic than tendons
- Best seen under tension
- Cortical attachment landmarks help localization



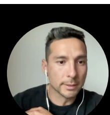
40

Key MSK Artifacts (Overview)

Artifacts Are Normal — Learn to Use Them

- Anisotropy
- Shadowing
- Acoustic enhancement
- Reverberation
- Side lobes
- Edge artifact

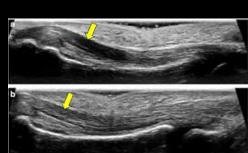
41



Anisotropy (Most Important MSK Artifact)

Angle-Dependent Brightness Loss

- Common in tendon, ligament, nerve
- Mimics tears
- Fix: heel-toe to maintain perpendicular angle



42

Shadowing

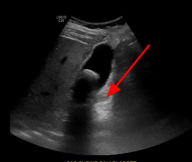
When Sound Cannot Penetrate

- Bone → clean shadow
- Calcification → dirty or clean shadow
- Foreign bodies → variable shadowing

43

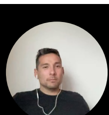
Acoustic Enhancement

Brighter Tissue Deep to Fluid



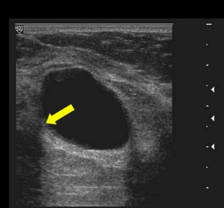
- Occurs beneath cysts, bursa fluid, effusion
- Helps distinguish solid vs cystic
- Enhances diagnostic confidence

44



Edge Artifact (Refraction at Curved Surfaces)

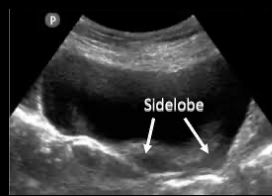
Shadowing at Curved Boundaries



On Slide:
- Seen at tendons, muscles, vessels
- Beam refracts around curved boundary → dropout

45

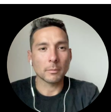
Side Lobe Artifact



False Echoes from Off-Axis Beams

- Echogenic debris in cysts
- Off-axis beams reflect into main image
- Importance in nerve scanning

46



Understanding Tissue Interaction = Accurate Interpretation

- Predictable tissue appearance
- Artifacts = diagnostic clues
- Angle dependency
- Tissue-specific expectations

47

References — Module 2

- Hedrick WR et al. *Ultrasound Physics and Instrumentation.*
- Kremkau FW. *Diagnostic Ultrasound: Principles & Instruments.*
- Hoskins PR et al. *Diagnostic Ultrasound: Physics & Equipment.*
- Szabo TL. *Ultrasound Imaging: Inside Out.*
- Fessell DP, van Holsbeeck M. *Ultrasound Clinics.*
- Thomas RH. *Semin Musculoskelet Radiol.*
- Jacobson JA. *Fundamentals of MSK Ultrasound.*
- Bianchi S, Martinoli C. *MSK Ultrasound.*

48

MODULE 3 — Pulse Echo Instrumentation & Imaging Principles

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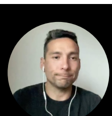
49

Module 3: Pulse Echo Instrumentation & Imaging Principles

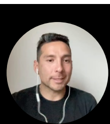
- Pulse formation
- Echo reception
- Signal processing
- Scan conversion
- Pre- & post-processing

50



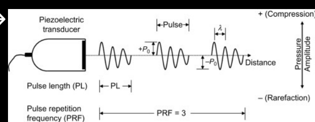
SECTION A — PULSE-ECHO BASICS

51



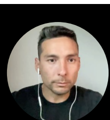
What Is Pulse-Echo Imaging?

Transmit → Wait → Receive → Process → Display



- One pulse at a time
- Listening time determines depth
- Echo intensity determines brightness

52



Range Equation (Depth Calculation)

- **Distance = (Speed × Time) / 2**
- Ultrasound assumes **1540 m/s**
- Time-of-flight determines depth
- Divided by 2 because sound travels there and back

Range Equation

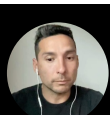
Speed of sound (soft tissue) 1540 m/s; Time (s)

$$D = \frac{C \cdot t}{2}$$

Depth (m); Return time (s)

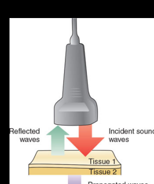
Range equation questions are common on the exam.

53



Reflection (Primary Image Creator)

Reflection = The Echoes We Turn Into Images



- Specular → tendon, bone cortex
- Diffuse → muscle, fat
- Angle-dependent (critical for MSK)

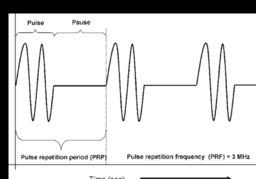
54

SECTION B — PULSE CHARACTERISTICS

55

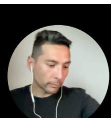
Pulse Repetition Frequency (PRF)

- **How Many Pulses Sent Per Second**
- ↑ PRF = ↑ frame rate
- ↓ PRF = deeper imaging
- High PRF risks **range ambiguity**

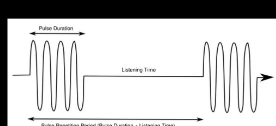


56

Pulse Duration



- **Length of Time the Pulse Is 'On**
- Shorter pulses = better axial resolution
- Determined by number of cycles × period
- Bandwidth and damping influence this

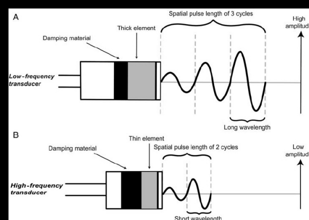


57

Spatial Pulse Length (SPL)

Physical Length of the Pulse in Space

- SPL = # cycles × wavelength
- Shorter SPL = better axial resolution
- Higher frequency = shorter wavelength

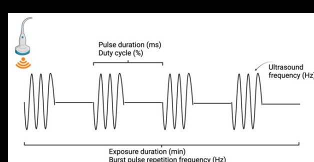


58

Duty Factor

Percentage of Time Ultrasound Is Transmitting

- Diagnostic US duty factor <1%
- Echo machine spends 99% of time listening
- Doppler increases duty factor



59

SECTION C — THE TRANSMITTER & RECEIVER

60

Transmitter (Output Section)

Controls Pulse Creation

- Determines:
- Pulse amplitude
- Pulse duration
- PRF

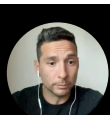
61

Receiver Functions Overview

How the Machine Processes Echoes

- Amplification
- Compensation
- Compression
- Demodulation
- Rejection

62



Amplification (Gain)

Boosting All Echo Signals Equally

- Does **not** increase transmitted power
- Makes entire image brighter
- Too much gain masks pathology

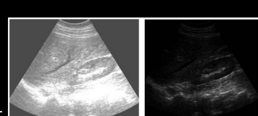


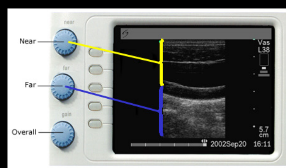
Fig 1 Overall gain set too high **Fig 2** Overall gain set too low

63

Compensation (TGC)

Corrects for Attenuation With Depth

- Adjusts brightness at specific depths
- Creates uniform image
- Essential for MSK



64

Compression

Reduces Wide Range of Echo Intensities

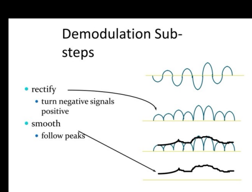
- Narrows signal dynamic range
- Makes image readable
- User control = dynamic range knob

65

Demodulation

Prepares Signal for Display

Two steps:
1. Rectification
2. Smoothing (enveloping)

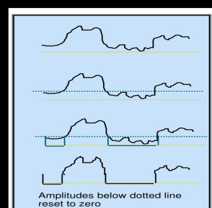


66

Rejection (Threshold)

Suppresses Low-Level Noise

- Eliminates unwanted echoes
- Too much → loss of detail



67

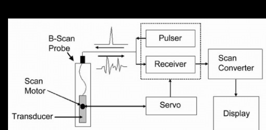
SECTION D — SCAN CONVERTER & DIGITAL PROCESSING

68

Scan Converter

Converts Echo Data Into Pixels

- Receives analog signals
- Stores digital values
- Uses X-Y grid for display



69

Preprocessing vs Postprocessing

Machine Decides vs User Decides

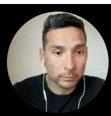
- Preprocessing:
  - Dynamic range
  - Persistence
  - Write zoom
- Postprocessing:
  - Map changes
  - Read zoom
  - Gray-scale curve

70

Preprocessing

- **TGC** (Time Gain Compensation)
- **Dynamic range (compression ratio)**
- **Persistence (frame averaging)**
- **Write zoom**
- **Edge enhancement** (if present)
- **Frequency compounding (if selectable)**
- **Spatial compounding**
- **RES-level adjustments** (line density changes)
- **Acoustic power**
- **Beam steering & focusing adjustments**

71



Postprocessing

User decides — can be changed anytime after the image is stored or frozen.

These include:

- **Gray-scale curve selection**
- **Map changes / color maps**
- **Read zoom**
- **Brightness & contrast display adjustments**
- **Smoothing filters applied after storage**

- These do **not** change the raw echo data.

72

SECTION E — REAL-TIME IMAGING LIMITATIONS

73

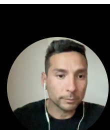
Frame Rate

Higher Frame Rate = Better Motion Imaging

Factors that increase frame rate:

- High PRF
- Narrow sector width
- Low line density
- Shallow depth

74

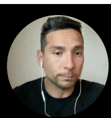


Temporal Resolution

Ability to Accurately Display Motion

- Improved by: shallow depth, narrow field, low line density
- Reduced by: high frame averaging, large sector widths

75



Things RMSK Will Test

Must-Know Exam Concepts

- Range equation
- Receiver functions
- Pre- vs post-processing
- PRF & depth relationship
- SPL & axial resolution
- Frame rate determinants

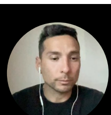
76

Summary

"Pulse → Process → Display → Interpret"

- Pulse creation
- Echo reception
- Signal processing
- Scan conversion
- Image optimization

77



Module 3 References

- Hedrick WR et al. *Ultrasound Physics and Instrumentation.* Elsevier.
- Kremkau FW. *Diagnostic Ultrasound: Principles and Instruments.* Elsevier.
- Hoskins PR et al. *Diagnostic Ultrasound: Physics and Equipment.* CRC Press.
- Szabo TL. *Diagnostic Ultrasound Imaging: Inside Out.* Academic Press.
- AIUM Official Statements on Instrumentation & Image Formation.
- Baker ML et al. *Ultrasound Clinics.* 2014.
- Athanasiou A et al. *Eur J Radiol.* 2012.

78